Very high cycle fatigue for single phase ductile materials: microplasticity and energy dissipation

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Very high cycle fatigue for single phase ductile materials: microplasticity and energy dissipation

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Abstract
The DISFAT project is a ongoing French project financially supported by the French National Agency ANR. It aims at a deeper understanding of mechanisms leading to crack initiation in ductile metals in Very High Cycle Fatigue (VHCF). The VHCF regime is associated with stress amplitudes lower than the conventional fatigue limit and numbers of cycles higher than 10^9. Tests were conducted using an ultrasonic technique at loading frequency of 20 kHz. The mechanisms leading to crack initiation express via slip bands at the specimen surface and self-heating due to intrinsic dissipation. Thermal maps were used to estimate the mean dissipation and its change with number of cycles and stress amplitudes in case of pure copper polycrystals. At the same time, the surface relief changes due to plasticity were characterized using optical and scanning electronic microscopes. A good correlation was found between slip band initiation and dissipation. Dissipation and slip band amount always increased over the number of cycles. At very small stress amplitudes, no slip band appeared up to 10^8 cycles but the material was found to dissipate energy. These results reveal that the material never reached a steady state. Therefore it could break at higher number of cycles.

Keywords copper, self-heating, slip bands, IR thermography, ultrasonic fatigue

1. Introduction

Nowadays there is a growing demand for the development of fast and robust fatigue life prediction methods in the very high cycle fatigue (VHCF) domain. The VHCF regime is associated with stress amplitudes lower than the conventional fatigue limit and as a result, numbers of cycles higher than 10^9. Some mechanical components, such as pistons, rotating axes, have been designed previously using fatigue resistance data at lower numbers of cycles ($<10^7$ cycles ; the regime of High Cycle Fatigue, HCF) whereas they must endure oscillating loads for a number of cycles higher than $>10^9$ cycles and finally fail [1]. These requirements motivate the need to understand the fundamental mechanisms of fatigue in the VHCF regime, correspondingly, to explore novel methods for the characterization of fatigue behavior at these very long lifetimes. The DISFAT project is an ongoing French project financially supported by the French National Agency ANR. It aims at a deeper understanding of mechanisms leading to crack initiation in metals and alloys in VHCF. Our strategy is first to analyze the response of metals and alloys having “simple” microstructure and deformation mechanisms but also controlled initial states, with special attention paid to the surfaces. From the existing knowledge of cyclic deformation mechanisms (High Cycle Fatigue range), we choose to study face-centered (fcc) and body centered (bcc) cubic metals and the role of two intrinsic properties of solid crystals: the tendency to wavy or planar slip and the lattice friction resistance. Second, the VHCF range is reached using ultrasonic fatigue machines. The working frequency is 20 kHz. The use of higher loading frequencies than conventional frequencies (~ 30 Hz) brings advantages (1) to reach the VHCF regime within a reasonable time and (2) to increase the dissipated power (energy per unit of time) and thus to generate temperature variations which can be detect with the current thermal measurement devices. Thus, the aim is to correlate surface dissipation field, surface relief changes due to the appearance of slip bands and plastic deformation mechanisms.

The project brings together four academic partners with complementary fields of expertise and equipments (PIMM – Arts et Métiers ParisTech, LEME - Université Paris X, LMGC - Université Montpellier II, LSPM – UPR CNRS). A technical center (CETIM Senlis) is also associated to transfer the results of this fundamental work to industrial applications. Most of participating researchers have worked in the HCF fatigue field and Professors Bathias and Mughrabi who contributed to the project provided pioneering and well-known works in the VHCF range. In this paper, we focus on results got for pure copper polycrystals. First, we explain our experimental procedure. Then, we introduce the calorimetric analysis. Finally, some results are presented in order to illustrate our methodology.

2. Experimental procedure

2.1. Materials and specimens

From the existing knowledge of cyclic deformation mechanisms [2-3], we choose to study the role of two intrinsic properties of solid crystals: the tendency to wavy or planar slip and the lattice friction resistance. In this project, we propose to study two classes of ductile single-phase metals with fcc and bcc structures. In both classes, we used a quasi-pure metal and alloys in order to change the ability to cross slip. Concerning bcc metals, low Fe-C, such as Armco iron, were used. Concerning fcc metals, pure copper and Cu-Zn (α-brass) alloys are good candidates. While pure Cu is known to deform with wavy slip, α-brass Cu-Zn displays planar slip [4-5]. Here, we only present results obtained on commercial polycrystalline copper CuOF 99.95% and α-brass Cu-15wt%Zn supplied by Griset Company.

In order to facilitate surface observation, a new hourglass shaped specimen with flat faces was designed (Fig. 1). The specimen dimensions were determined so that all the parts, such as transmission and amplification pieces, vibrate at a resonance frequency of 20 kHz in tension-compression [6-7]. After mechanical and electrolytic polishing, the specimen surfaces were mirror finished without any residual stresses. The stress distribution along the specimen axis (calculated numerically) is presented in Fig. 1. The stress is concentrated in the middle of the gauge part of the specimen and reduced toward the specimen ends. This geometry allows to systematically study the material response at all desired stress amplitudes with one single specimen.

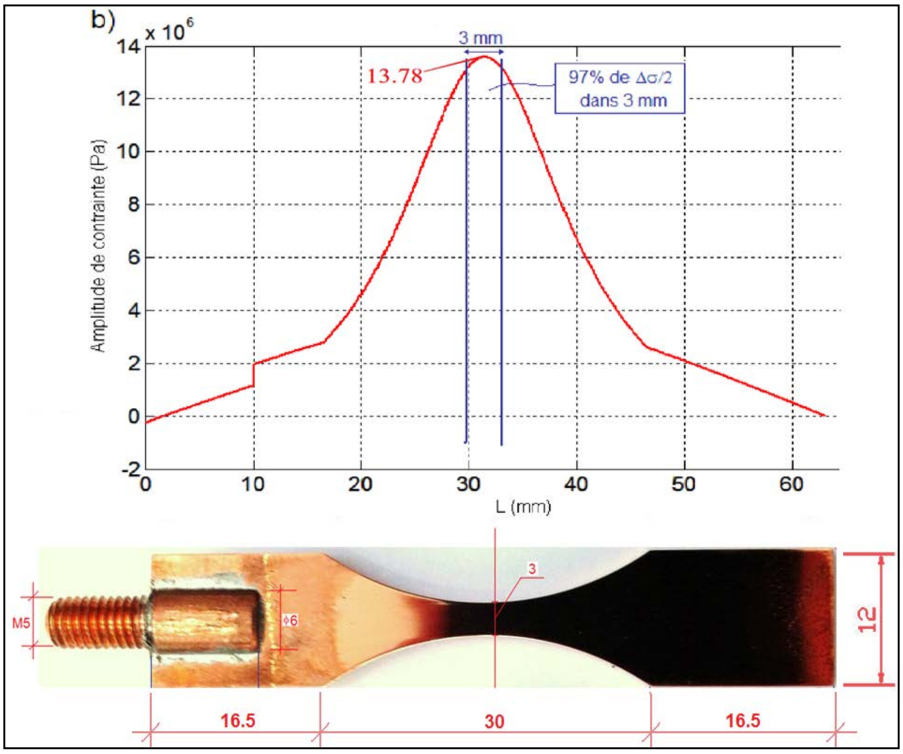

Figure 1. Ultrasonic fatigue plate specimen and distribution of stress along the specimen axis

2.2. Fatigue tests

The experimental setup involves the mechanical testing machine shown in Fig. 2. It essentially involves 3 components [1]:

- a piezoelectric system that transforms an electrical signal into a displacement
- an ultrasonic horn which amplifies this displacement (usually 3 to 9 times)
- a specimen screwed on the horn and free of stress at its bottom extremity.

This dynamic loading system is designed, assuming an elastic behaviour, in order to have a longitudinal vibration mode at a frequency of around 20 kHz. In order to obtain the relation between the displacement on the horn edge and the input electrical signal, the testing machine is calibrated with a laser extensometer.

During fatigue tests, an infrared camera (512x640 pixels) monitors the temperature field on the specimen surface. A pixel calibration is performed before each new test. The specimen surface is painted in matte black to have a uniform surface emissivity close to 1. Spatial resolution is about 0.1 mm/pixel. From the temperature measurements, the intrinsic dissipation was determined using a 1D heat diffusion model (see the following section).

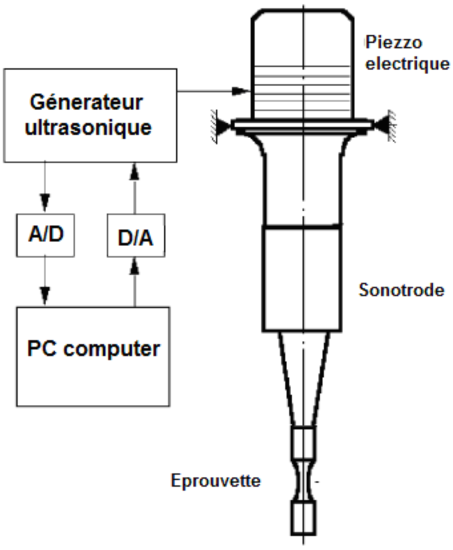

Figure 2. Scheme of the piezoelectric machine

3. Calorimetric analysis

3.1. Model of heat diffusion

A numerical model was built to estimate the evolution of intrinsic dissipation from temperature measurement fields during the fatigue test. We focused on the longitudinal distribution of heat sources within the specimen gauge part. A 1D calorimetric analysis has been justified assuming in a first approximation a uniaxial tension-compression stress state. From the heat equation:

$$\rho C\,\dot{T} - k\Delta T = s \tag{1}$$

where T is the temperature, ρ the mass density; C the heat capacity; k the thermal conduction coefficient. s(x,y,z,t) symbolizes the volume of heat source. Following Boulanger's hypotheses [8], the 1D diffusion equation for a non-constant cross-section can be written as [9]:

$$\frac{\partial\theta(x,t)}{\partial t} + \frac{\theta(x,t)}{\tau^{1D}(x)} - \frac{k}{\rho C}\left(\frac{\partial^2\theta(x,t)}{\partial x^2} + \frac{\partial\theta(x,t)}{\partial x}\frac{S'(x)}{S(x)}\right) = \frac{s(x,t)}{\rho C} \tag{2}$$

with $\theta = T - T°$ is the temperature change, $T°$ is the room temperature and τ^{1D} is a time constant term which characterizes the heat losses through lateral surfaces of the specimen*:*

$$\tau^{1D}(x) = \frac{\rho C\cdot S(x)}{2h(e+l(x))} \tag{3}$$

where e is the specimen thickness, *l(x)* is its width with respect to *x*. We note by $S(x) = e\cdot l(x)$ the cross-section at this point. The mean dissipation over several thousand cycles was solely estimated (the thermo elastic sources being not considered here regarding the test frequencies and the adiabatic character of the thermoelastic processes over a complete cycle duration (50 µs)). In the above equations, the unknown parameter is the heat transfer coefficient *h*. The method used to identify *h* is presented in the following section.

3.2. Heat loss time constant identification

The heat transfer coefficient is determined for each test, from thermal field measurements when the fatigue loading is stopped and the temperature of specimen returns to thermal equilibrium. More precisely, the initial temperature was considered as the temperature when the load was stopped. During the thermal return to equilibrium, no heat source occurs. Thermal measurements θ^{exp} applied to each end of the specimen by Dirichlet method enabled us to know the boundary conditions. The unknown heat transfer coefficient *h* was well chosen to satisfy these conditions:

$$\begin{cases} \dfrac{\partial\theta(x,t)}{\partial t} + \dfrac{\theta(x,t)}{\tau^{1D}(x)} - \dfrac{k}{\rho C}\left(\dfrac{\partial^2\theta(x,t)}{\partial x^2} + \dfrac{\partial\theta(x,t)}{\partial x}\dfrac{S'(x)}{S(x)}\right) = 0 \\ \theta(x,t=0) = \theta^{\exp}(x,t=0) \\ \theta(\dfrac{-L}{2},t) = \theta^{\exp}(\dfrac{-L}{2},t) \end{cases} \quad (4)$$

As a result, *h* was found in ranges of 30 – 100 W/m^2/K. This result shows that the heat losses are caused by natural convection and also by an air flow above the specimen which aims at cooling the piezoelectric system.

4. Results for polycrystalline pure copper and discussions

Fig. 3a and 3b display the average temperature over the gauge length and several thousands of cycles and the corresponding intrinsic dissipation for various maximum stress amplitudes versus the number of cycles for CuOF 99.95%. The temperature rises over cycles and never reaches a constant value. In other words, the temperature does not stabilize, showing an evolution of the heat balance and consequently of the microstructure. Despite a slight raise of the temperature at $\Delta\sigma/2$= 44.1 MPa, the intrinsic dissipation increased very slowly with the number of cycles. It attained to 0.498 °C/s at 10^6 cycles and reached 0.505 °C/s at 10^8 cycles. It means that the heat sources were higher than the heat losses and remained active along the cycles. However, no slip bands were observed on specimen surface up to 10^8 cycles at this stress range. At $\Delta\sigma/2$ = 49.6 MPa, the intrinsic dissipation increased slowly up to 10^7 cycles. No slip bands were either observed between 10^6 and 10^7 cycles. At 10^8 cycles, a clear increase of the intrinsic dissipation was recorded and slip markings were observed on the specimen surface. The intrinsic dissipation was 1.322 °C/s (Fig. 4a). At higher stress amplitude, $\Delta\sigma/2$= 54.7 MPa, the intrinsic dissipation increases with the number of cycles more rapidly than in previous cases. First slip bands were observed at 10^7 cycles (Fig. 4b). They are more pronounced at 10^8 cycles (Fig. 4c). At $\Delta\sigma/2$ = 69.4 MPa, the intrinsic dissipation rises very fast with the number of cycles and reaches 7.477 °C/s at 10^6 cycles. First slip bands were observed at 10^6 cycles (Fig. 4d). The roughness and the quantity of slip bands kept rising over the cycles as dissipation (Fig. 4e and 4f). At 10^7 cycles, the narrowest zone of the specimen was covered with slip bands and the specimen self-heating is about 70°C.

In addition to average values, the intrinsic dissipation distribution can be estimated along the specimen axis (Fig. 5a). The intrinsic dissipation is concentrated in the middle of the specimen and decreases toward the ends. As expected, it is related to the distribution of stress (Fig. 1). Optical micrographs revealed that this zone displays the highest quantity of slip markings (Fig. 5b). This result confirms that dissipation is related to microplasticity.

4. Conclusions

The DISFAT project is an ongoing French project financially supported by the French National Agency ANR. It aims at a deeper understanding of mechanisms leading to crack initiation in metals and alloys in Very High Cycle Fatigue (VHCF). Thermal maps were used to estimate the mean dissipation and its change with number of cycles and stress amplitudes in case of pure copper polycrystals. At the same time, the surface relief changes were characterized using optical and scanning electronic microscopes. A good correlation was found between slip band initiation and dissipation. Dissipation and slip band amount always increased over the number of cycles. They are higher with increasing stress amplitudes. The 1D dissipation distribution is in good agreement with the stress 1D profile. The strongest dissipation value was found at the place where the number of slip bands is the highest. At very small stress amplitudes, no slip band appeared up to 10^8 cycles but the material was found to dissipate energy. These results reveal that the material never reached a steady state. Therefore it could break at higher number of cycles.

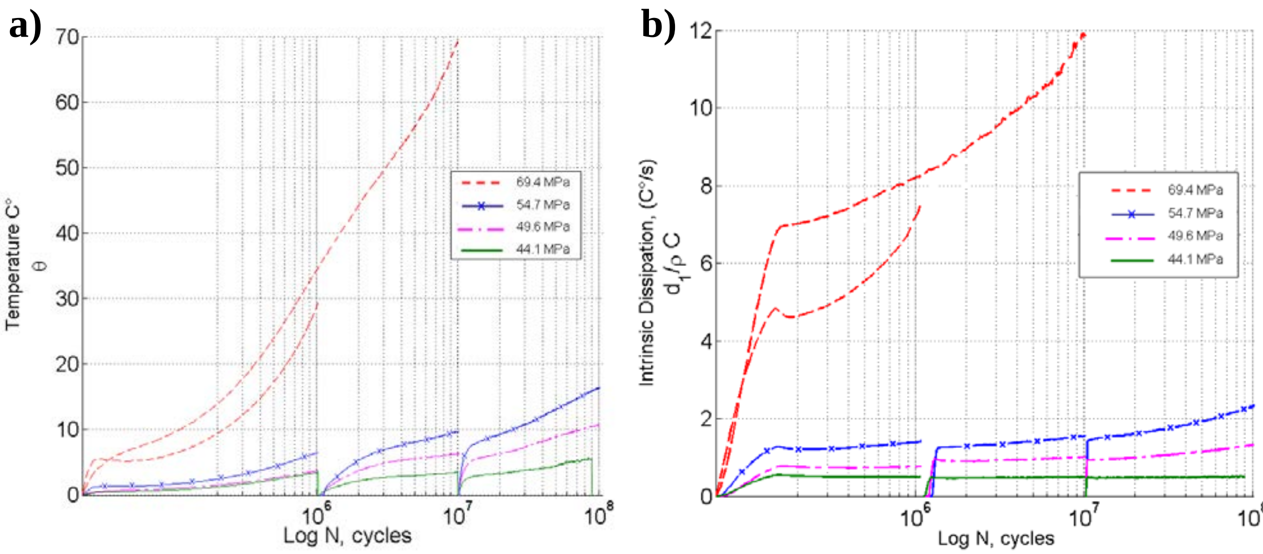

Figure 3. (a) Average temperature and (b) Average intrinsic dissipation during fatigue test at different constant stress amplitude fatigue test for CuOF 99.99%.

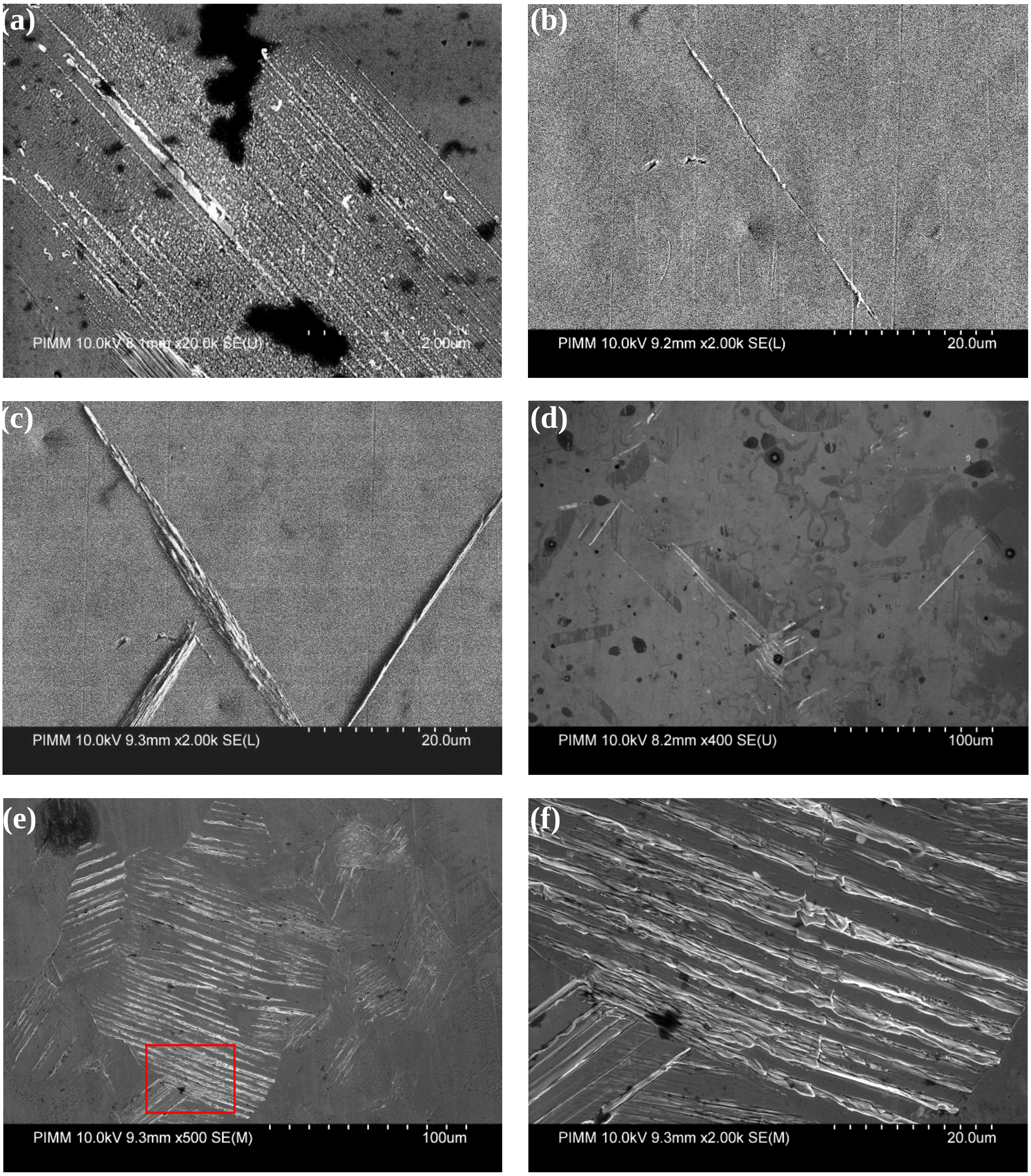

Figure 4. Scanning Electron Micrographs of the specimen surface - (a) $\Delta\sigma/2$ = 49.6 MPa - 10^8 cycles;
(b) $\Delta\sigma/2$ = 54.7 MPa - 10^7 cycles and (c) at the same place after 10^8 cycles;
(d) $\Delta\sigma/2$ = 69.4 MPa - 10^6 cycles; (e) $\Delta\sigma/2$ = 69.4 MPa - 10^7 cycles
(f) zoom of (e)

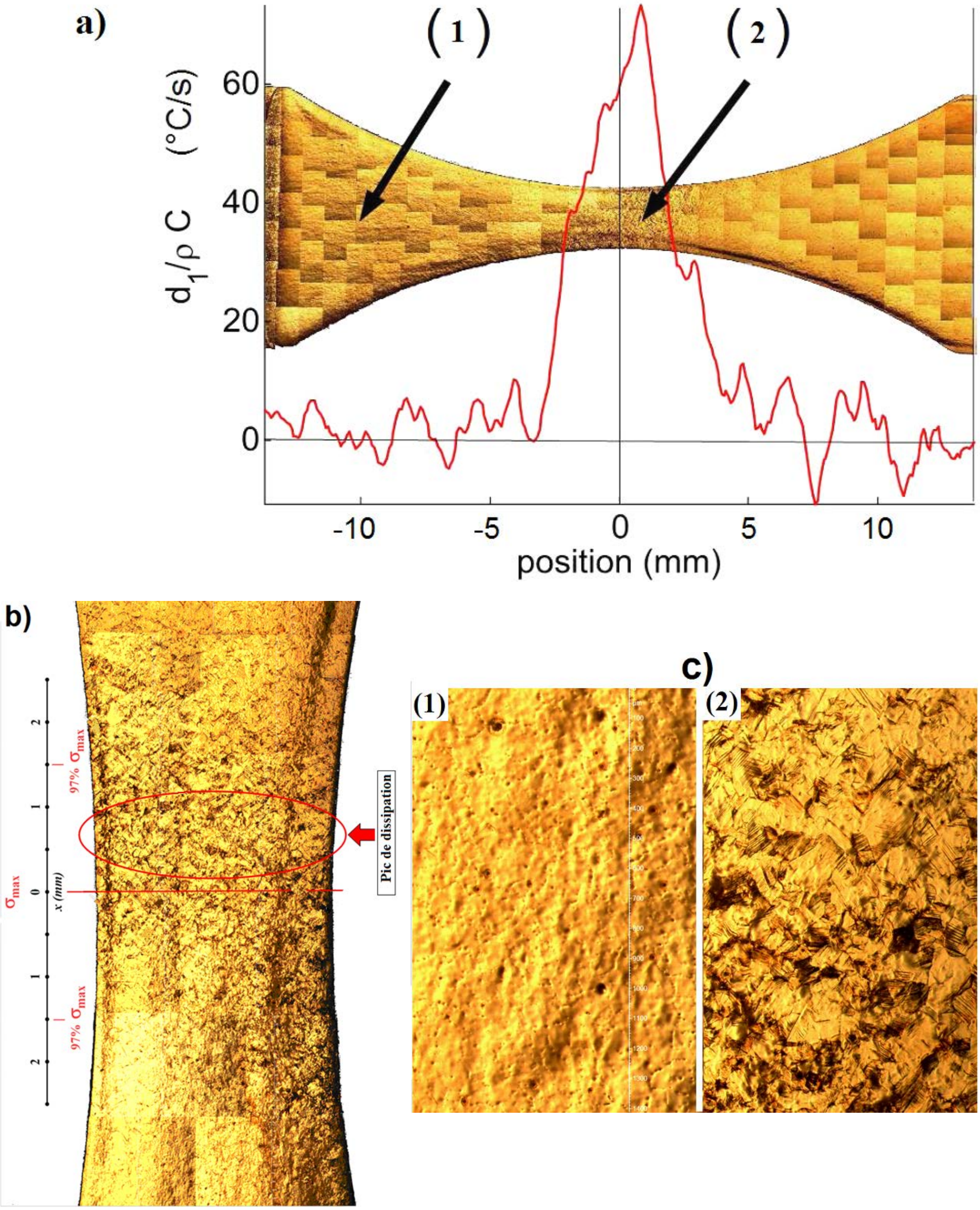

Figure 5. a) 1D distribution of the intrinsic dissipation along the specimen
b) Optical micrograph of the middle part of the specimen c) Optical micrographs at two places of the specimen surface (noted (1) and (2))
at $\Delta\sigma/2 = 69.4$ MPa - 10^7 cycles

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